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Review

Environmental and economic comparison of hydrogen fuel cell and battery electric vehicles

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ABSTRACT

The study of alternative energy sources has accelerated over the years. Further investigation of alternative energy sources is important for reasons that are unknown and unthought about by people around the world. Many sources of energy that are not renewable energy sources are harmful to the environment and are causing a high rise in greenhouse gas (GHG) emissions. If society would learn more about the increase of carbon emissions and their effects on the environment, then there could be a drop in these emissions. Transportation has been one of the largest sectors of GHG emissions and has not seen a large enough decrease to be substantial enough to better the environment. The transportation sector of the GHG emissions could be easily fixed with the use of hydrogen fuel cells or battery electric vehicles. The idea of fuel cell and battery electric cars has been around for decades but has only recently become popular. The increase in these vehicles will cause a decrease in greenhouse gasses produced by transportation. This paper compares hydrogen fuel cell and battery electric vehicles economically and environmentally.

1. Introduction

On a global basis, there are approximately one billion vehicles on the road today. According to recent projections, this number could climb to 1.5 billion automobiles by 2020. The continuous economic expansion and industrial development of China and India are primarily responsible for this considerable growth. Even though the car ownership rate in these two countries is still fairly low, both markets have recently become quite important for the global automotive sector. China is already the single largest market for numerous automobile manufacturers [1]. The current transportation system, which relies primarily on fossil fuels, is unsustainable [2]; more than 95% of the fuel utilized for propulsion is derived from fossil fuels [1]. On-road carbon dioxide (CO_2), nitrogen oxide (NO_x), and particulate matter (PM) are disproportionately represented by conventional HDVs [3]. In the United States, medium and heavy-duty vehicles account for roughly 23% of greenhouse gas (GHG) emissions [4]. Heavy-duty diesel vehicles (HDVs) are also responsible for 40–60 percent of NO_x and PM emissions. Climate change, pollution, and the resulting health effects are just a few of the key concerns associated with the increase in combustion emissions. Because of the widespread use of HDVs, greenhouse gas emissions from the freight transportation industry are a substantial contributor to climate change, pollution, and poor health effects [3]. Greenhouse gas emissions are not the only reason that renewable energy sources are needed in the transportation vector. Oil depletion is going to play a big role in removing internal combustion engines from the roads. Even the most modern conventional powertrain alternatives will not be able to prevent an increase in overall crude oil demand by the transportation sector, which will eventually contribute to an increase in world CO_2 emissions. Because of a 50 percent rise in demand for oil, CO_2 output is unacceptably high in terms of cost, environmental impact, and energy security. Every automotive technology strategy must incorporate the substitution of fossil fuels as energy carriers [1]. Transportation end-use sector emissions come from a variety of sources, including automobiles, trucks, commercial airplanes, and railroads, among others [4]. Figure 1 portrays the overall percentage of GHG emissions of each automobile. As a result, the development and adoption of more sustainable alternatives are being promoted [2]. Alternatives to diesel engines include battery electric HDVs and hydrogen fuel cell HDVs. Each HDV powertrain, whether it's a diesel engine HDV, a battery-electric HDV, or a hydrogen fuel cell HDV, has its own set of benefits and drawbacks [3].

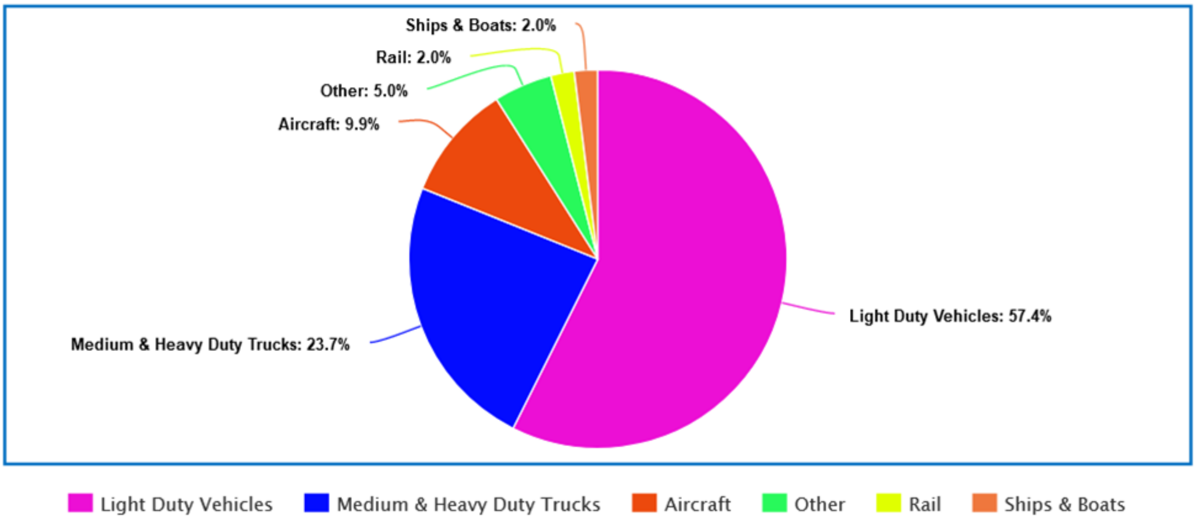

Figure 1. The overall percentage of GHG emissions of each automobile [2]

2. Impact on the environment

The impact on the environment is a large hurdle to cross when dealing with any type of transport vehicle. If cars were to keep using internal combustion engines, then the carbon emissions would continue to increase based on the increase in population and the demand for transportation. This would mean that by 2100 the temperature increases of the world based on global warming could be close to 3°C [5]. This means that in the parts of the world that already get up to 54°C (130°F) it could rise to temperatures that are not safe for the human body to withstand for more than a few hours. If no amendments were set into place to improve climate change, many of the beautiful parts of the world such as the rainforests and other woody areas, would not be able to thrive, which would then cause multiple species of plants and animals to become extinct. In 1970 the Clean Air Act was passed by the congress of the United States. This caused a limit to the pollution and greenhouse gas emissions for many different companies. This act is not the best way to decrease greenhouse gasses and global warming, but it is a way to lower what could have been if nothing were to change [6].

3. How the vehicles are powered

i. Battery Electric Vehicles: The way the BEV runs are a simple circuit. The electricity stored by the battery runs straight to the motor. From this, the well-to-wheel efficiency is very high. The electricity goes straight from the grid to the battery to the motor [7]. There is no transportation necessary for this well-to-wheel efficiency. The issue with this model is that it does not directly show where the electricity is starting from. If the electricity is produced at a plant that burns coal, then the process is not fully free from producing greenhouse gasses [8]. As of 2021, electricity production from renewable energy sources has been rising, but the bulk of electricity is still created by coal and natural gas. Both sources still create a large amount of carbon emissions, even though natural gas creates half as much as burning coal does [9]. This means that the BEV does not totally reduce the carbon footprint as some consumers may think. Carbon emissions could easily be lowered if electricity production switched to renewable energy sources such as solar panels or wind turbines. Both options are increasing in efficiency and production, so the switch to renewable energy is predicted to happen within the next ten to twenty years [5].

ii. Hydrogen Fuel Cell Vehicles: Hydrogen fuel cell vehicles (HFCV) are powered purely by hydrogen gas. The hydrogen powers the electric motor by separating the electrons inside the fuel cell stack. Inside the fuel cell stack is an anode that forces the electrons to separate from the hydrogen molecule. These electrons then follow a different path than the protons that can slip through the anode. While the protons pass through the anode and move through an electrolyte to the other side of the cell where there is a cathode, the electrons pass through an external circuit, creating electricity. The proton then passes through the cathode and combines with the oxygen in the air and the electrons [10]. This process explains why the only output of the hydrogen fuel cell is water (H_2O) and heat. It is notable that water vapor is still a greenhouse gas and is the most abundant greenhouse gas [7]. However, water vapor is essentially a harmless greenhouse gas since it does not stay in the atmosphere if other greenhouse gasses such as carbon dioxide. Additionally, carbon dioxide holds heat in the atmosphere much longer than water vapor. This is not only because it stays in the atmosphere longer, but because it potently absorbs and radiates this heat [11].

4. Cost

Kromer and Heywood at MIT have analyzed the likely costs of various alternative vehicles in mass production [12]. They conclude that an advanced battery EV with a 320 km (200 miles) range would cost approximately $10,200 more than a conventional car, whereas an HFCV with a 560 km (350 miles) range is projected to cost only $3,600 more in mass production. Plug-in hybrid electric vehicles (PHEVs) with only 16 km (10 miles) all-electric range would cost less than the HFCV, but plug-in hybrids with 100 km (60 miles) range are projected to cost over $6,000 more than conventional gasoline cars. If we extrapolate the Kromer and Heywood data for BEVs to 480 km (300 miles) range, then the BEV would cost approximately $19,500 more than a conventional car in mass production [7]. For example, Pedro and Putsche [13] estimate that using wind energy, hydrogen production costs alone will amount to US$ 20.76 per tank to

drive our FCV 300 miles compared to US$ 4.28 "per tank" (or per charge) for the BEV. The cost per tank is based on the Padro and Putsche estimate of US$ 6.49 per kg to produce the 3.2 kg of hydrogen necessary to power the FCV for 300 miles and US$ 0.055 cents per kWh to provide the 77.9 kWh required to power the BEV for 300 miles [13]. Maintaining the same performance assumptions, we next compare the projected relative weight, volume, and unit costs of each vehicle's propulsion system. The results are reported in Tables 1 and Table 2.

Table 1. Estimated weight, on-board space, and mass-production cost requirements of the FCV propulsion system [14]

Component	Weight (kg)	Volume (l)	Cost (US $)	Reference
Fuel Cell	617	1182	23,033	ADL (2001)
3.2 kg storage tank	51	215	2,288	Padro and Putsch (1999)
Drivetrain	53	68	3.286	AC Propulsion Inc. (2001), Solectria Corp (2001)
Total	721	1465	29147	

Table 2. Estimated weight, on-board space, and mass-production cost requirements of a BEV propulsion systems [14]

Component	Weight (kg)	Volume (l)	Cost (US $)	Reference
Li-ion battery	451	401	16,125	Cuenca and Gains (2000)
Drivetrain	53	68	3.286	Cuenca and Gains (1999)
Total	504	469	19,951	

When interpreting the tables, it is important to note that the limiting factor in HFCV performance is the amount of power that can be delivered, which affects vehicle acceleration and hill-climbing. For BEVs, the limiting factor is the amount of energy that can be delivered, which affects the total vehicle range. This means that the scaling factors for weight, volume, and cost for the HFCV are based on how many Watts (of power) that can be delivered per unit of weight, volume, or cost. For the BEV it is the amount of Watt-hours (of energy) that can be delivered per unit of weight, volume, or cost. The cost of vehicle fuel (electricity or hydrogen) per km driven will depend on the fuel price per unit of energy and the vehicle fuel economy. The residential price of electricity is projected by the DOE's Energy Information Administration in their 2009 Annual Energy Outlook to be approximately 10.8 cents/kWh during the 2012–2015 period, which corresponds to $31.64/MBTU [15]. The NRC estimates that hydrogen will cost approximately $3.30/kg by the time of hydrogen fueling system breakeven or $29.05/MBTU. Costs of fuel per unit of energy will be comparable once the hydrogen infrastructure is in place. Initially, without government subsidies, hydrogen costs would be much greater before there are enough HFCV on the road to provide energy companies with a reasonable return on investment. In addition, many BEV owners may receive lower off-peak electricity rates if they charge their batteries at night. As shown in Table 3, the cost per mile for a BEV owner with the off-peak rate of 6 cents/kWh will be approximately half the cost of hydrogen fuel per km for an HFCV owner. This lower fuel cost when off-peak rates are available would help to offset the higher initial price of the BEV. But the buyer of a 320-km (200-mile) BEV would still pay $1042 more for that vehicle including off-peak electricity at 6 cents/kWh to run it for 15 years than the purchaser of a 560-km (350-mile) range HFCV would pay including 15 years of hydrogen fuel. A buyer of a 480-km (300-mile) BEV would spend $11,315 more over 15 years.

Table 3. Estimated fuel cost (cents per kilometer) for battery EV drivers and fuel cell EV drivers [15]

Range	Electricity		Hydrogen
(km)	6 cents/kWh (off-peak)	10.8 cents /kWh (Residential)	($3.30/kg)
161	1.37	2.47	3.33
241	1.41	2.54	3.35
322	1.53	2.75	3.36
402	1.67	3.00	3.38
483	1.85	3.34	3.40

5. Fueling Infrastructure Cost

The 2008 National Research Council report estimated that a hydrogen fueling station based on reforming natural gas would cost approximately $2.2 million when produced in quantities of 500 or more [1]. This station would support approximately 2300 HFCV, so the average infrastructure cost per HFCV would be $955. The initial stations will cost more, on the order of $4 million each, which represents a cost of $1700 per vehicle when HFCVs were first introduced [7]. To disseminate the use of fuel-cell vehicles as well as to minimize the costs, it is necessary to determine if hydrogen production, storage, and distribution methods were playing a crucial role [16]. In 2050, production and distribution in liquid form will reduce the price of hydrogen when compared to today's preferred hydrogen gasification technology [17]. Adding a residential Level 1 (120 V, 20 A) charging outlet is estimated to cost $878 by Idaho National Laboratory [12], but this capacity would require charging times of 43 h for 320 km range and 78 h for 480 km range. A higher capacity Level 2 outlet (240 V, 40 A) would cost about $2150 for a home residence and $1850 for a commercial outlet. This would reduce charging times to 11 h for 320 km range, and 19 h for 480 km range. A residential charging outlet could, in principle, be used to charge two or more BEV, since only one BEV in a family would likely be required to travel the long distances in a particular period of a day or two. A Level 2 outlet would most likely be unable to service more than one or two BEV in a business day. The expected capital costs for long-range BEV charging outlets, therefore, varies between $880 and $2100 per BEV. While the capital costs per vehicle are comparable once fueling systems are

deployed, more drivers could have access to electricity initially than access to hydrogen fueling stations. An individual BEV owner who can pay $2100 for a Level 2 home charging outlet fixture will be able to utilize his or her car within half the vehicle range from home even if no other driver has a BEV in the area. A driver contemplating the purchase of an HFCV, however, would generally require at least one hydrogen fueling station within five or 10 kilometers of home. Most potential HFCV owners could not afford own hydrogen fueling stations [18]. We assume that some combination of government and private investment would supply the capital to build the initial batch of hydrogen fueling stations, starting in clusters around a group of major metropolitan cities. Governments would be motivated to jump-start the hydrogen fueling systems to reap the huge societal benefits that will follow from the introduction of large numbers of zero-emission fuel cell EVs. Private investors will eventually be motivated to build new hydrogen fueling stations since the return on investment will be very lucrative once there are many HFCVs on the road [7].

6. Refueling Times

As different types of alternative energy-powered vehicles are created, it is well known that battery electric vehicles are the ones to beat. BEV's have started to become favored over internal combustion engines by those who are trying to reduce their carbon footprint. The BEV runs purely on a battery charged by a station that many owners can have the option to buy for their home. The option to have this charging station at home is the optimal solution due to the longer than desired charging times [19]. Depending on the charging station, the BEV can take between thirty minutes up to multiple hours to fully recharge the battery. On the other hand, internal combustion engines (ICE), take only three to five minutes to refill. This issue does not tend to stop people from purchasing the BEV since it is an option to buy a charging station for their home. This means that the vehicle could charge overnight if the need arises. Like the ICE, hydrogen fuel cell vehicles only take three to five minutes to refill. This quick recharge could potentially knock the BEV from its pedestal as the best alternative for renewable energy-powered vehicles [20]. As shown in Figure 2, China has the most fueling stations for battery electric vehicles in both the fast and slow charging methods. These statistics are from the 2021 statistics census. Figure 3 indicates that Japan has the largest amount of hydrogen fueling stations. Overall BEVs have a much larger amount of fueling stations. The cost of the infrastructure is the dominating issue for hydrogen fuel. This is talked about in the cost section. Once the fueling stations can catch up to the number of stations the BEVs have, there will not be an issue with refueling hydrogen fuel cells [21]. Many arguments have been made towards hydrogen fuel cell vehicles (HFCV) just based on how there is no infrastructure, but at a time there was no infrastructure for BEVs. HFCVs can easily have a large increase in fueling stations once the infrastructure can be paid for [19].

7. Types of Battery

a. Lead-acid battery: The lead-acid battery is the most mature kind of battery. It is made up of stacked cells immersed in a dilute solution of sulfuric acid (H_2SO_4) as an electrolyte. The positive electrode of each cell is composed of lead dioxide (PbO_2), while the negative electrode is sponge lead (Pb). During discharge, both electrodes are converted into lead sulfate ($PbSO_4$). During the charge cycle, both electrodes return to their initial state [22]. There are two major kinds of lead-acid batteries: flooded batteries and valve-regulated batteries. The lifetime of the system is approximately 5–15 years, with an energy efficiency of 75–80%.

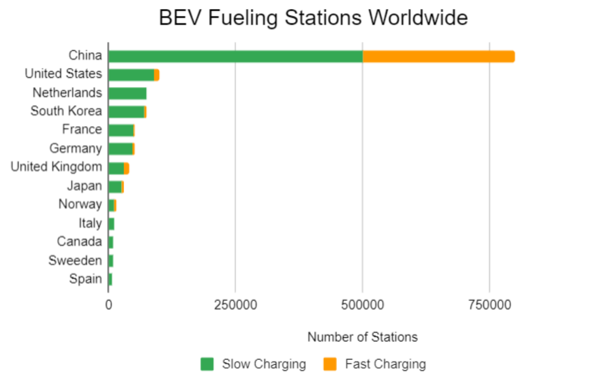

Figure 2. Amount of electric recharging stations by country in 2021 [21]

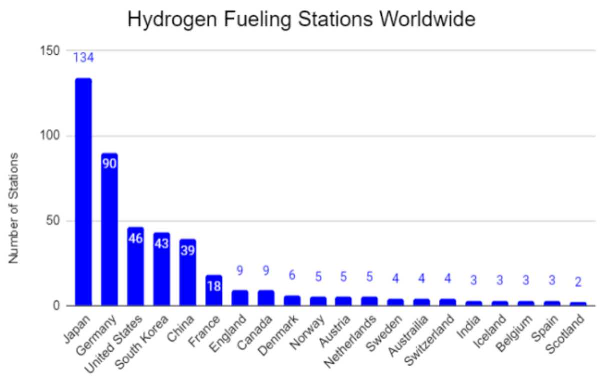

Figure 3. Amount of hydrogen fueling stations by country in 2021 [21]

b. Nickel-cadmiumium battery (Ni-Cd): Development of this kind of alkaline rechargeable battery has been carried out since 1950. This has helped to make them a well-established system in the marketplace. The main components of Ni-Cd batteries are nickel species and cadmium species as the positive and negative electrodes' active materials, respectively, and aqueous alkali solution as the electrolyte [23]. During the discharge cycle, $Ni(OH)_2$ is the active material of the positive electrode, and $Cd(OH)_2$ is the active material of the negative electrode. During the charge cycle, NiO(OH) is the active material of the positive electrode, and metallic Cd is the active material of the negative electrode. The alkaline solution KOH acts as the electrolyte. The Ni-Cd battery has suitable characteristics with respect to its long cycle life (more than 3500 cycles), combined with low maintenance requirements [18]. Nevertheless, its cycle life is highly dependent on the depth of discharge (DD). It can reach more than 50,000 cycles at 10% of DD [24].

c. Sodium–sulfur battery (NaS): Besides being a relatively recent system, NaS batteries are one of the most

promising options for high-power energy storage applications [24]. The anode of this kind of battery is made of sodium (Na), while the cathode is made of sulfur (S). Ceramic Beta– Al2O3 acts as both the electrolyte and the separator simultaneously [25]. During the discharge cycle, the metallic anodic material (sodium) is oxidized and releases NaS ions, while the cathodic material is reduced and releases S_2 sulfur anions. The electrolyte enables the transfer of sodium ions to the cathode, where they combine with sulfur anions and produce sodium polysulphide Na_2S_x. During the charge cycle, the opposite reaction occurs [26]. An important feature of this type of battery is its high-temperature operation, around 350°C. One of the largest manufacturers of NaS batteries is the Japanese company NGK insulators [27]. The energy density and the energy efficiency of this kind of battery are very high, 151 kW h/m3 and 85%, respectively [28]. Additional important features of NaS batteries are no self-discharge, low maintenance, and their 99% recyclability [24].

d. Lithium-ion battery (Li-ion): Lithium-ion batteries are widely used in small applications, such as mobile phones and portable electronic devices; therefore, the annual production gross is around 2 billion cells. In addition, this kind of battery attracts much interest in the field of material technology and others to obtain high-power devices for applications like electric vehicles and stationary energy storage [24]. The operation of Li-ion batteries is based on the electrochemical reactions between positive lithium ions (Li^+) with analytic and catalytic active materials. The cells of Li-ion batteries are made of analytic and catalytic plates filled with liquid electrolyte material. The electrode areas are delimited by a porous separator of polyethylene or polypropylene, which allows the transit of lithium ions. During the charge cycle, Li^+ flows from the positive electrode, made of $LiCoO_2$, to the graphite sheets of the negative electrode. The discharge cycle consists of the reverse process. Since the performance and the range size of the batteries are strongly related to the active materials of the electrodes and the electrolyte, there is a tremendous amount of research in the field of material technology nowadays [29]. Important features of Li-ion batteries are time constants (understood here as the time to reach 90% of the rated power of the battery) around 200 ms, with a relatively high round trip efficiency of 78% within 3500 cycles have been reported [30]. Moreover, nickel, manganese, and cobalt are used in most lithium-ion batteries in electric vehicles [8].

e. Lithium Iron Phosphate (LFP) battery: Lithium Iron Phosphate battery (lithium ferro phosphate or lithium iron phosphate) is a type of lithium-ion battery using lithium iron phosphate ($LiFePO_4$) as the cathode material and a graphitic carbon electrode with a metallic backing as the anode [31]. The energy density of an LFP battery is comparatively lower. Because of its lower cost, high safety, low toxicity, long cycle life, and other factors, it is a good potential replacement for lead-acid batteries in applications such as automotive and solar applications, utility-scale stationary applications, and backup power [32]. LFP batteries are cobalt-free [33]. One important advantage over other lithium-ion chemistries is thermal and chemical stability, which improves battery safety. $LiFePO_4$ is highly resilient during oxygen loss, which typically results in an exothermic reaction in other lithium cells [34]. As a result, $LiFePO_4$ cells are harder to ignite in the event of mishandling. EV giants, Tesla, and Ford are going to employ LFP batteries in at least some of their vehicles, which are popular in China [8].

f. Solid State battery: Solid-state batteries use solid electrodes and a solid electrolyte and lack a liquid electrolyte, making them lighter, storing more energy, and charging more quickly; moreover, they are less prone to catch fire, requiring less cooling equipment [8]. Solid-state batteries can provide potential solutions for many problems of liquid Li-ion batteries, such as flammability, limited voltage, unstable solid-electrolyte interphase formation, poor cycling performance, and strength [35]. This battery provides higher energy densities and avoids the use of dangerous or toxic materials found in commercial batteries [38]. Other EV giants Volkswagen and BMW have both invested in and are implementing this technology [10].

8. The Colors of Hydrogen

Because there are many different methods to produce hydrogen, a schematic to separate hydrogen and how it impacts the environment has been constructed.

a. Gray Hydrogen (Steam Methane Reformation [SMR]): The first color of hydrogen is the largest percentile of the colors. This method uses steam methane reformation to produce hydrogen. Gray hydrogen is the leading hydrogen production method that, if used in the automotive industry, would produce a large amount of greenhouse gas emissions including CO_2. This means that while the production method may be efficient, it is not the best method for producing hydrogen since it would contribute a similar amount of greenhouse gasses that internal combustion engines create while driving on the roads now. SMR produces hydrogen with two chemical reactions which are [37]:

Steam-Methane Reform

$$CH_4+H_2O \rightarrow CO+3H_2 \quad (1)$$

Water-Gas Reaction

$$CO+H_2O \rightarrow CO_2+H_2 \quad (2)$$

Steam methane reformation has other problems with the production rather than simply being harmful to the environment. It does not create pure hydrogen, which is needed for hydrogen fuel cells. Gray hydrogen also consists of coal gasification due to the high amount of CO_2 that is produced in this method of hydrogen production [35]. Coal gasification is used in larger countries such as China and India. Production from coal gasification is an issue because there is no way to isolate the carbon that is being developed from the reaction. Coal is being carbonized so the carbon emission for this method is one of the highest out of all the different options. This method of steam methane reformation and coal gasification does not separate out the CO_2 and store it like it would in the next section of blue hydrogen [37].

b. Blue Hydrogen: Blue hydrogen uses the same method of steam methane reformation, but with the option of carbon capture and storage. Issues with this method have been noted by the laws of capturing carbon. To be named as blue hydrogen the steam methane process does not need to fully capture all the carbon dioxide that is separated. Implementing the carbon capture is sufficient to name the hydrogen as better for the environment, but still produces a

large amount of CO_2 over time [20]. This process of carbon capture also produces a large amount of methane emissions. Noted by Ajanovic et al. [38], blue hydrogen still produces half the emissions as gray hydrogen since there is a greater methane leak after carbon capture is implemented. Environmental acts are not only focused on the emissions of carbon dioxide but other greenhouse gasses as well. In general gray and blue hydrogen is not the best implication of hydrogen production since fuel cells require pure hydrogen to not disturb the catalysts that are used inside of them. To make the pure hydrogen, carbon capture and storage is necessary. Carbon capture bases its system on natural gas and oxygen to separate the carbon dioxide. This ends in pure hydrogen, but in the end, creates a large amount of CO_2 emissions. Again, these emissions are in fact a similar amount that is made from the internal combustion engines that are on the roads today. If this method of hydrogen production was used, then it would be better off to have battery electric vehicles since there would then be less CO_2 emissions from batteries.

c. Green and Yellow Hydrogen: Applications of green hydrogen include hydrogen that is produced from water by electrolysis. Electrolysis consists of a machine called an electrolyzer which uses water to separate the atoms (H_2O) and form hydrogen (H_2) and oxygen (O) atoms. If the source that powers the electrolysis is a renewable resource such as solar or wind energy, then this method of production will create zero greenhouse gas emissions. This creates the thought of yellow hydrogen which produces no CO_2 during the process [20]. If the electrolyzer is powered by other forms of electricity production, such as burning fossil fuels, then greenhouse gasses will be produced. When greenhouse gasses are produced from fossil fuels, the color of hydrogen is green [38]. According to Brenda Johnston et al. [9], electrolysis is not the most efficient operation for large-scale hydrogen production. This is because it uses a large amount of electricity. Issues could be explored and established by constantly using a renewable energy source to fuel production. If the renewable energy sources are connected to a battery that can collect that electricity, then this issue could be resolved. In the end, it is possible to produce hydrogen without creating greenhouse gasses if the right method is used. Opposing the thoughts of Johnston et al., when using the most environment-friendly option of electrolysis, the hydrogen is in the purest form of 99.99% hydrogen. No other hydrogen-producing method can obtain pure hydrogen, so this method could be labeled the most efficient and environmentally safe option for producing hydrogen.

9. Well to Wheel Efficiencies Using Natural Gas

a. Well to Pump: The efficiencies will be compared using the natural gas model. Using this model will ensure that the amount of carbon emissions is the same for both types of vehicles. Implementing this model for both vehicles will enhance the comparability of the efficiencies. When using the natural gas model, it is notable that hydrogen is more efficient. As shown in Figure 4, steam methane reformation has an efficiency of 75%, while for battery electric vehicles, the efficiencies are around 40% if using a generator [21]. Studies have shown that it would take half a million more BTUs to use natural gas to generate electricity than it would produce hydrogen. So, in total, it would take around 35% less energy to create hydrogen than energy for battery electric vehicles. If the range of the vehicles were to rise by just 50 miles, then hydrogen production would be even more efficient than electricity production using this method of natural gas. In this scenario, hydrogen production would take up to 55% less energy than electricity production [6].

b. Pump to Wheel: On the other side of the well-to-wheel efficiency, batteries seem to be on the leading end of things. As shown in Figure 5, batteries have around a 90% efficiency in delivering the power to the motor. This is because the electricity is going straight from the battery to the motor. Hydrogen has only a 52% efficiency from the pump to the wheel based on how indirectly the electricity is made throughout the hydrogen fuel cell. The fuel cell has more components which leads to less of a power input than the direct power of the battery [20]. When looking at this schematic, it is important to not just look at one side of the efficiency but the efficiencies. From well-to-wheel hydrogen fuel cells take up less total energy consumption. Based on the longest ranges of vehicles that can be produced, the longer the range the more efficient fuel cells are than battery-electric [39]. This was said in the well-to-pump section but is important in this section of well-to-wheels since batteries drain quicker than hydrogen is used inside of the fuel cell.

10. Well to Wheel Efficiencies Using Renewable Energy

Renewable energy sources have a significant role in reducing carbon emissions. With renewable energy sources, there is no need to use oil or natural gas in the production of either hydrogen or electricity. When renewable energy is used for hydrogen, it will power the electrolyzer to turn water into hydrogen, creating green hydrogen talked about in previous sections. If renewable energy is used for electricity production, then the electricity can go straight to the grid so it could refuel the batteries inside of the vehicles almost directly [21].

a. Well to Pump: Renewable energy sources have higher efficiency for both hydrogen and electricity production. As shown in Figure 5, electricity production has a well-to-pump efficiency of 92%. This means that nearly all the electricity produced can go straight to the pump for the electric vehicles. For hydrogen, there is only a 75% efficiency. This efficiency loss is due to the electrolyzer. When the electricity is used to power the electrolyzer to produce the hydrogen for the pump, the loss of 15% efficiency happens [20]. It is notable that the electrolyzer efficiency loss is like the loss when using steam methane reformation (SMR). This could lead the public to believe that electrolysis is not any better than SMR, but based on carbon emissions, electrolysis is the most eco-friendly option. Similarly, in the natural gas production method, if the range of the vehicles were increased, then the efficiencies would change. For the battery electric vehicle, the efficiency would decrease; and for the hydrogen fuel cell vehicle, the efficiency would increase [39].

b. Pump to Wheel: The pump-to-wheel section for renewable energy sources is the same as the one for natural gas production methods. Similarities are found because from the pump to the wheel, the electricity and hydrogen run through the vehicles the same way. From this, we can see the same as before where the electricity to the battery vehicle's wheels has a higher efficiency than hydrogen to fuel cell vehicles wheels [39].

11. Conclusion

Knowing that the oil industry will eventually end or become one of the most expensive fueling options, it would be best to switch to an alternative. Both BEV and HFCV have their drawbacks, but overall, HFCV is the leading option. When dealing with the cost of the materials, hydrogen, in the end, will be the cheaper alternative fuel source by half the amount per tank. While there are not many fueling stations for hydrogen, after development, the benefits of the fueling stations would overpower the multiple fueling stations for BEVs by around $2000 per at-home charging station. Along with the fueling cost, refueling times for HFCV have the advantage. Refueling times for HFCVs are like those of gasoline that is used today, around three to five minutes. The fastest BEV charging stations are up to thirty minutes, but they cost up to $2000 more than the charging stations that take hours to recharge the vehicles.

Environmentally, BEVs and HFCVs are similar in ways, but the HFCVs can be the most environmentally friendly option. There are many ways to isolate hydrogen. When electrolysis is used, there are no carbon emissions. This method will need electricity to operate, but if renewable energy sources are used, then this option is fully carbon-free. Because alternative energy sources such as solar panels and wind turbines do not emit CO_2, the BEV and HFCV are equally environmentally friendly. However, when batteries are made, the materials used are unfavorable to those that are used inside a hydrogen fuel cell. Since electricity can be produced with these environmentally friendly options, this is when the efficiencies come into action. While the electrolyzer slightly decreases efficiency, the distribution of hydrogen is more efficient than the distribution of electricity due to travel. Overall, it is notable that hydrogen fuel cell vehicles are more economical and environmentally friendly.

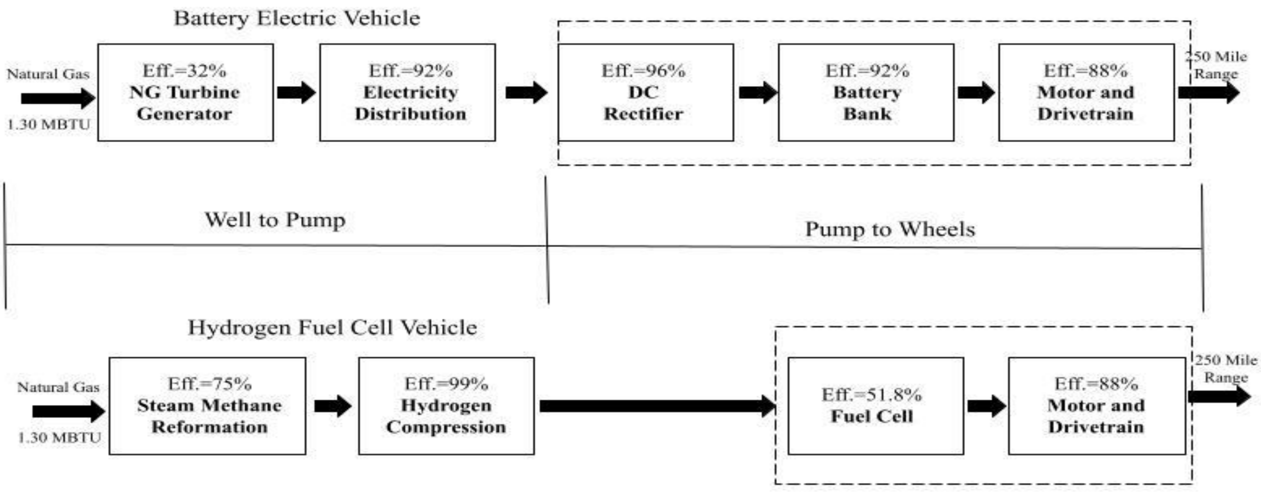

Figure 4. Efficiency chart comparing BEV to HFCV when using natural gas as the initial source [6]

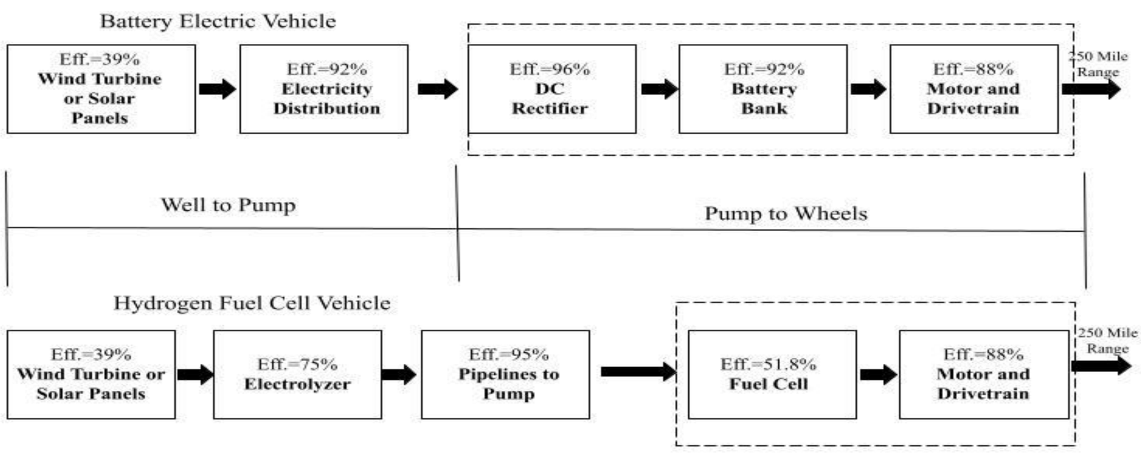

Figure 5. Efficiency chart comparing BEV to HFCV when using renewable energy as the initial source [39]

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. Authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Conflict of interest

The authors declare no potential conflict of interest.

Authors' contribution

All authors of this study have a complete contribution to manuscript writing.

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